
The Water Shield for the Daya Bay Reactor Neutrino Experiment

Princeton Meeting on Water Shields for DUSEL, 7/28/2008

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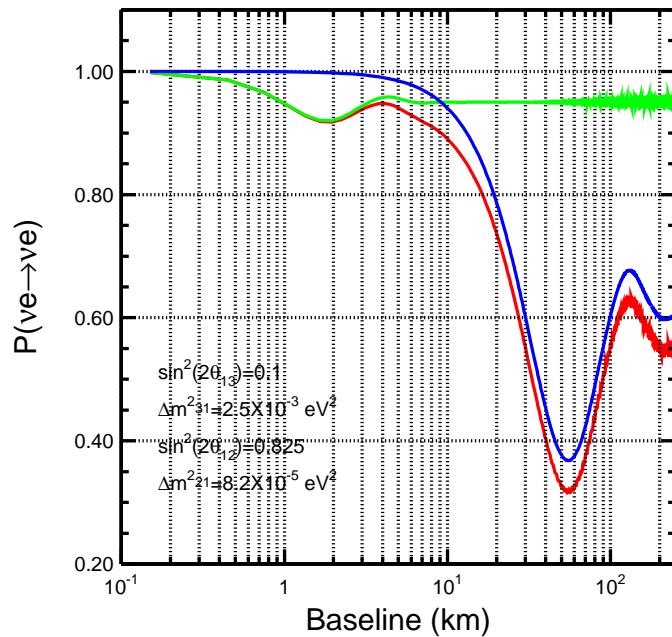
Brookhaven National Lab.

OVERVIEW OF THE DAYA BAY EXPERIMENT

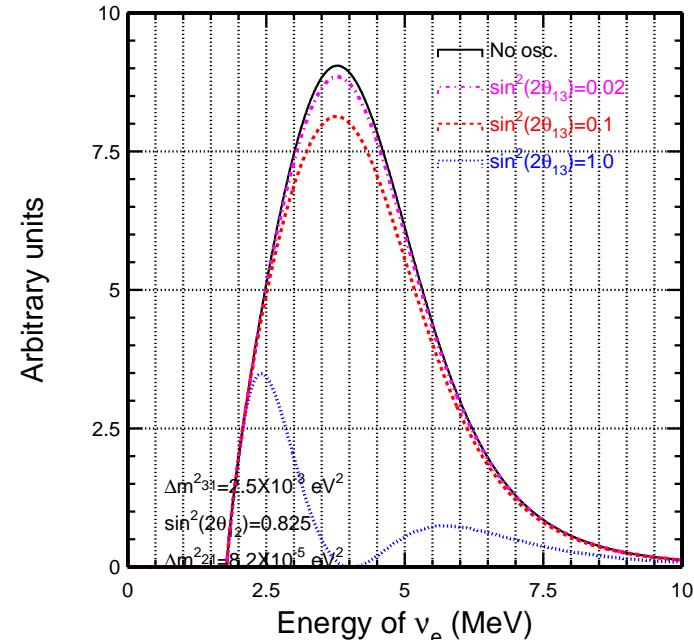
Reactor $\bar{\nu}_e$ oscillations

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{31}^2 L/E) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m_{21}^2 L/E)$$

Osc prob. (integrated over E) vs distance

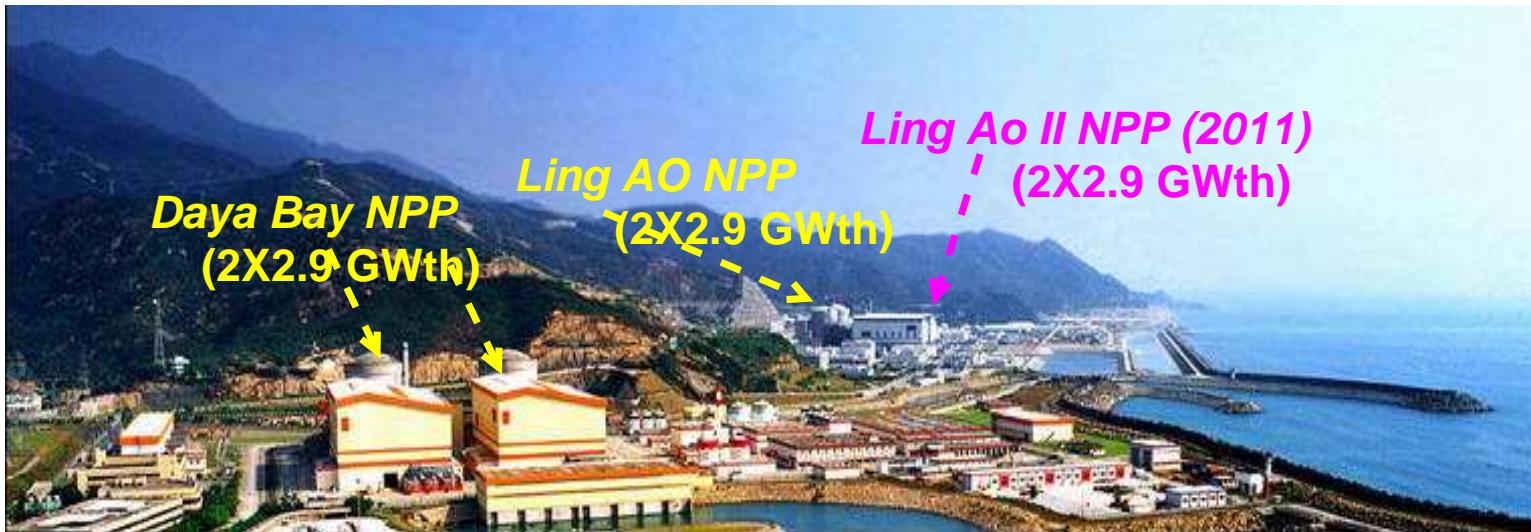


Osc. spectrum at 2km



Reactor ν_e disappearance = unambiguous measurement of $\sin^2 2\theta_{13}$

The Daya Bay Reactor Complex



Reactor Specs:

Located 55km north-east of Hong Kong.

Current: 2 cores at Daya Bay site + 2 cores at Ling Ao site = 11.6 GW_{th}

By 2011: 2 more cores at Ling Ao II site = 17.4 GW_{th} ⇒ 5th most powerful in the world

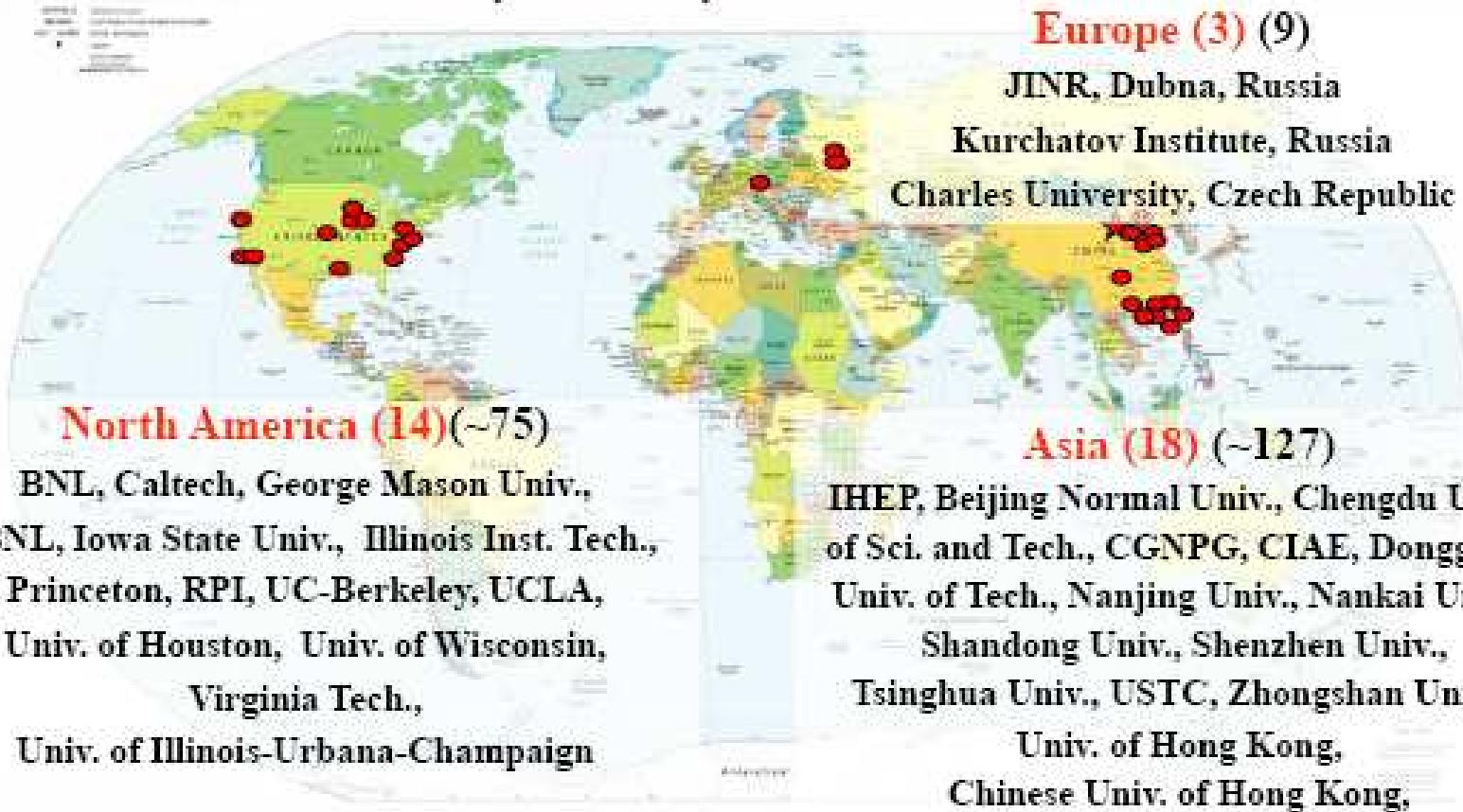
$$1 \text{ GW}_{th} = 10^{20} \bar{\nu}_e / \text{second}$$

Deploy multiple near and far detectors



In World, June 1999

The Daya Bay Collaboration



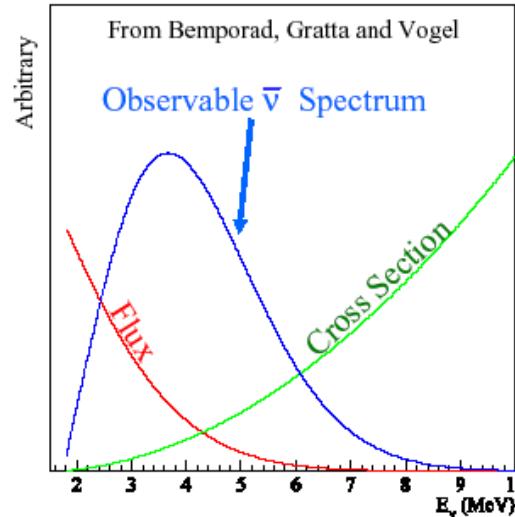
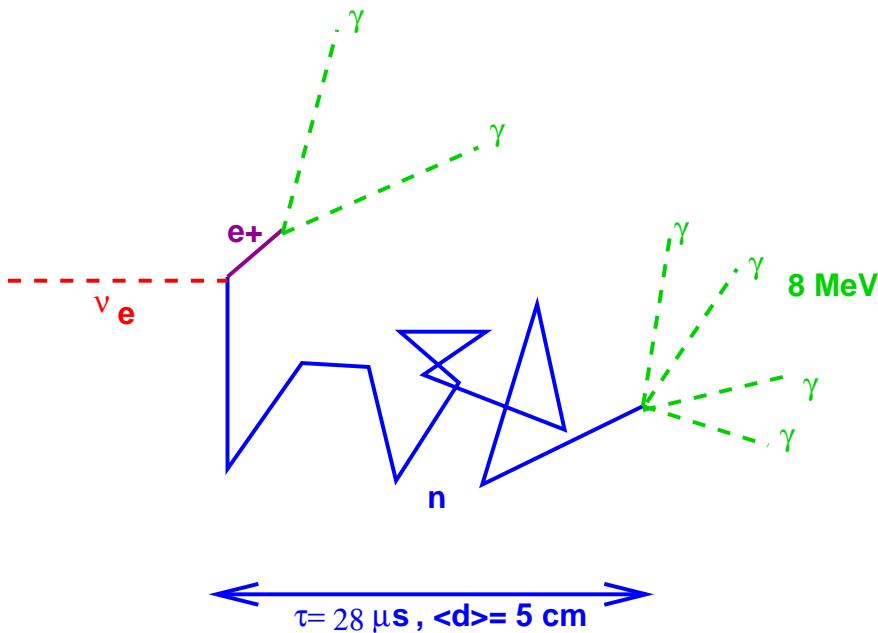
~ 211 collaborators

Daya Bay ground breaking 10/14/07, CD3b review 7/10/08



Detecting $\bar{\nu}_e$ using GD-loaded LS.

The active target in each detector module is liquid scintillator loaded with 0.1% Gd



The detection sequence is as follows: $\bar{\nu}_e + p \rightarrow n + e^+$ THEN
 $e^+ + e^- \rightarrow \gamma\gamma$ (2X 0.511 MeV + T_{e^+} , prompt)
 $n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma$'s (8 MeV, $\tau \sim 28 \mu\text{s}$, $\sigma = 5 \times 10^4 \text{ b}$). OR
 $n + p^+ \rightarrow D + \gamma$ (2.2 MeV, $\tau \sim 180 \mu\text{s}$, $\sigma = 0.3 \text{ b}$).

⇒ delayed co-incidence of e^+ conversion and n-capture

with a specific energy signature

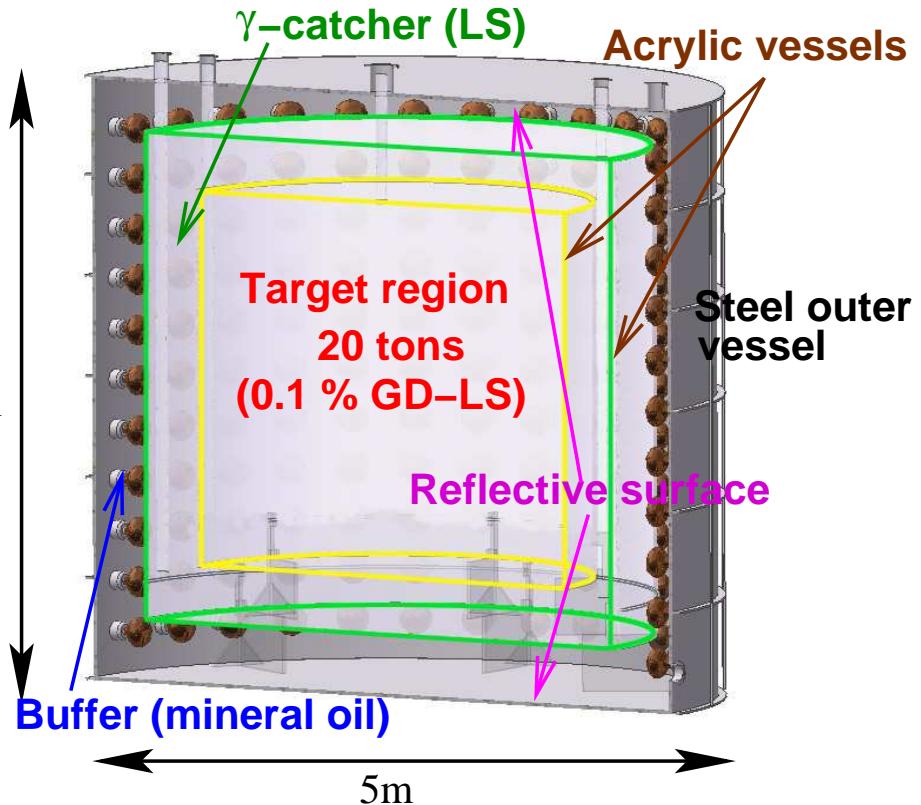
The Anti Neutrino Detector

3 zone nested cylindrical structure with the following specifications:

192 8" PMTS are mounted around the circumference of the outer steel tank with diffuse reflectors on top and bottom: (effective coverage 12%)

$$\frac{\sigma}{E} \sim \frac{12\%}{\sqrt{E(\text{MeV})}}$$

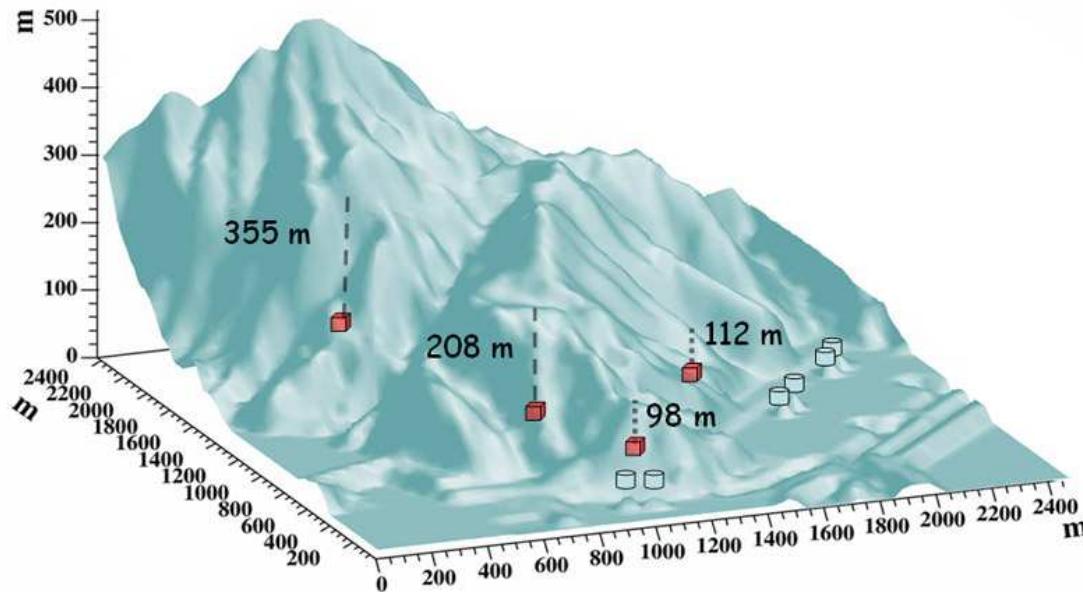
$$\sigma_{pos} = 13 \text{ cm}$$



	DYB	LA	Far
Event rates/20T/day	930	760	90

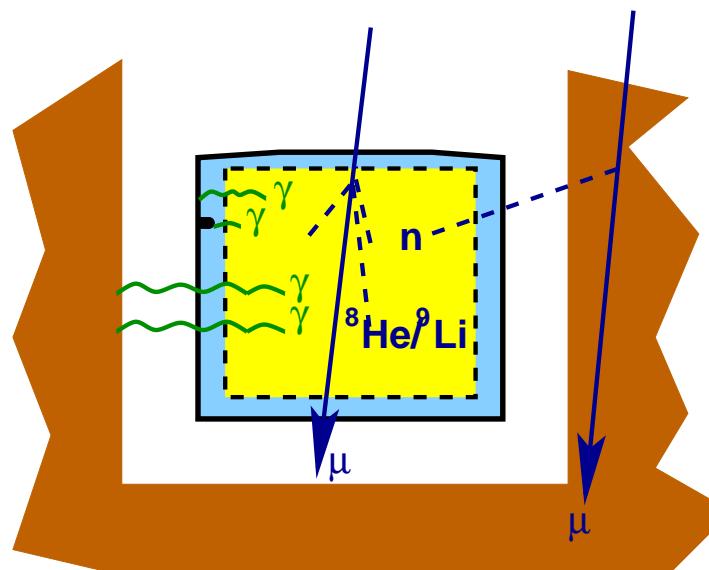
Cosmic Ray Flux

- Used a modified Gaisser parametrization for cosmic-ray flux at surface
- Apply MUSIC and mountain profile to estimate muon intensity and energy



	DYB	LA	Far
Overburden (m)	98	112	355
Muon intensity (Hz/m^2)	1.16	0.73	0.041
Mean Energy (GeV)	55	60	138

Background sources in the AD

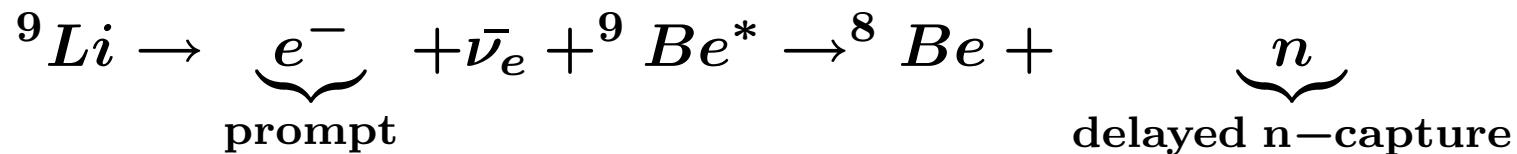


Source	Type	Rate/20T module/day (DYB/LA/FAR)
Rock	$\text{U/Th/K } \gamma > 1 \text{ MeV}$	$\mathcal{O}(\text{MHz}) \text{ w/o shielding!}$
SS vessel and welds	U/Th/K/Co	$\sim 20 \text{ Hz}$
PMT glass R5912	U/Th/k	$\sim 12 \text{ Hz}$
Cosmic muons	$^{12}\text{B}/^{12}\text{N } \beta$ only	396/267/28
Cosmic muons	$^{8}\text{He}/^{9}\text{Li } \beta\text{-n}$	3.7/2.5/0.26
Cosmic muons	fast neutrons (2 subevents)	depends on shielding
Cosmic muons	neutrons (1 subevent)	depends on shielding

GOAL: Use water shield to reduce coincident bkgd rate to $< {}^8\text{He}/{}^9\text{Li}$

He^8/Li^9

Generated by showers from cosmic muons:



$Q = 13 \text{ MeV}$, $\tau = 178 \text{ msec} \Rightarrow$ poor spatial correlation with μ track.

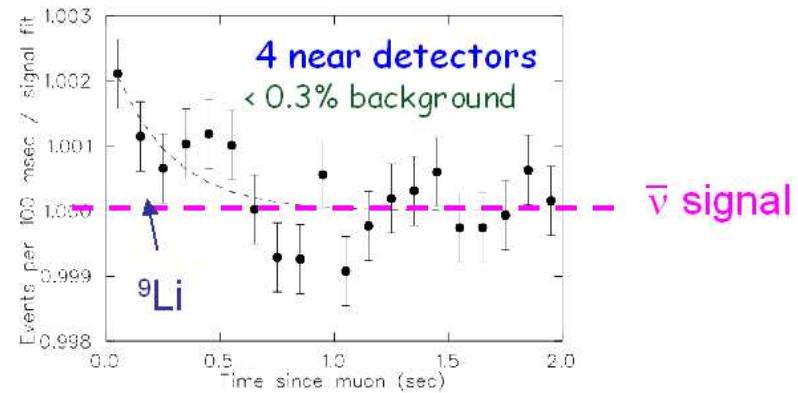
Computed rates (Hagner et. al.) :

	DYB	LA	Far
${}^9\text{Li} + {}^8\text{He}$ rates/module/day	3.7	2.5	0.26

But it can be measured ! →

$\sigma(B/S) = 0.3\%(\text{near})$

0.1% (far):

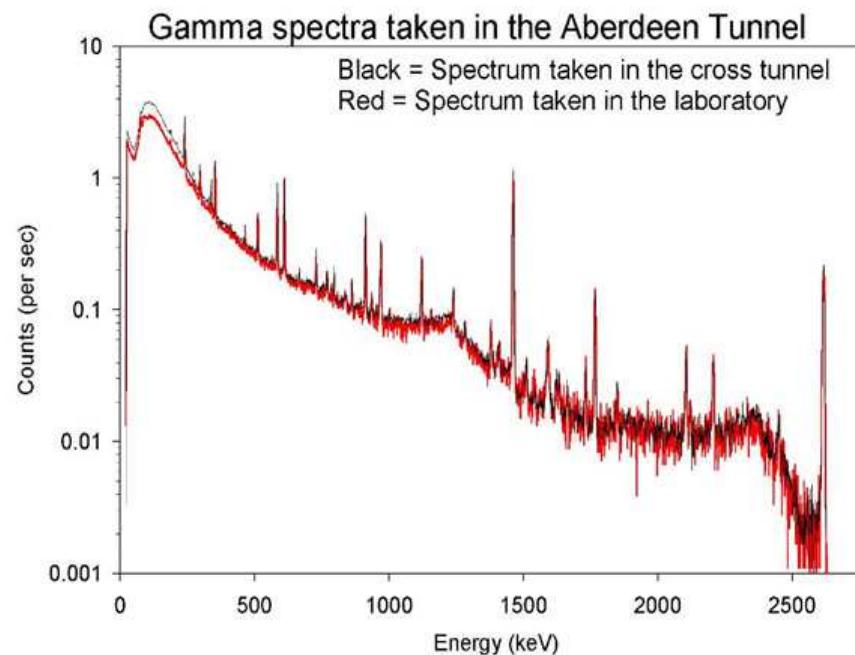


Time since muon (sec)

Rock Radioactivity

Daya Bay granitic rock is very radioactive!

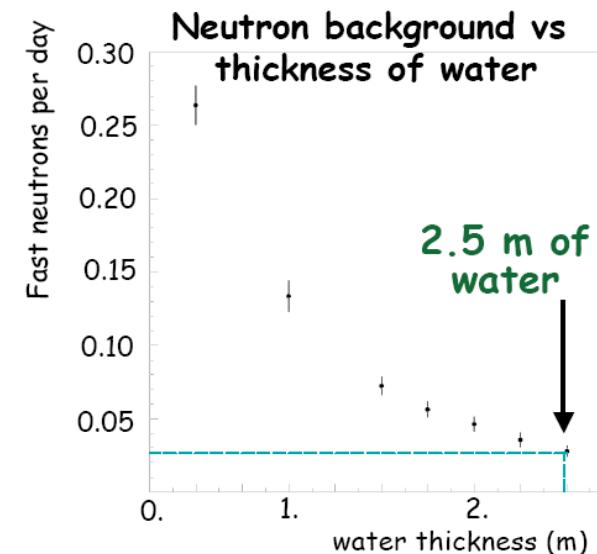
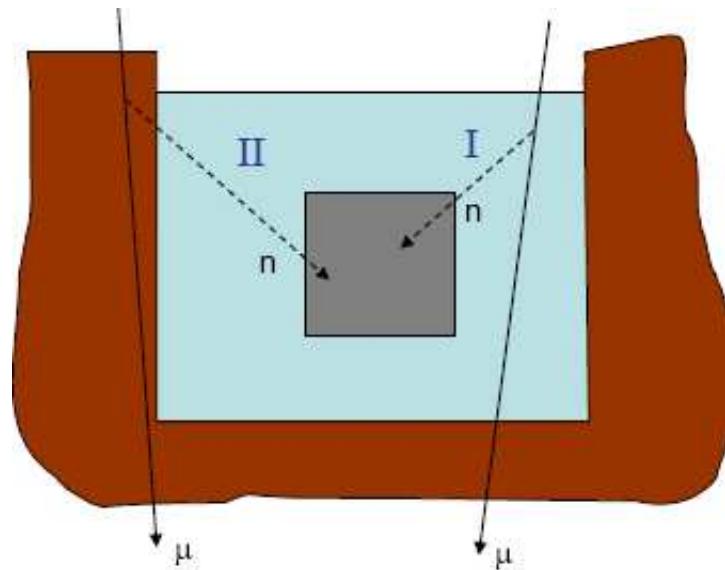
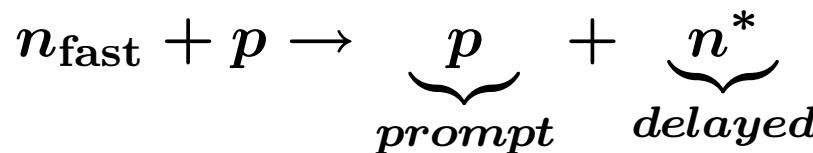
Measured U/Th/K \approx 10ppm/30ppm/5ppm in samples. Also measured the spectrum from the Aberdeen tunnel in HK (same type of rock):



Low-E γ from radioactivity = x10 reduction for every 50 cm H₂O.

2.5m water and 45cm mineral oil buffer \sim 3.5 Hz/20T module

Fast Neutron Background



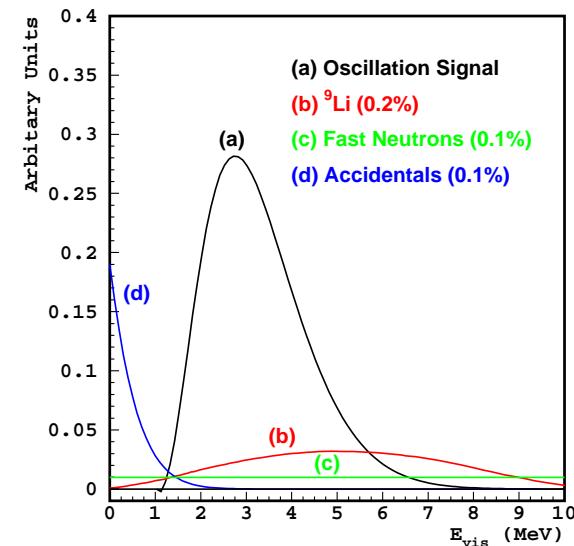
Fast neutron simulation results assuming active water shield with 99.5% muon tagging eff (events/day/20T module) :

	I: From untagged μ	II: Rock neutrons	II: Total/Signal
DYB	0.10	0.5	6×10^{-4}
LA	0.07	0.35	6×10^{-4}
Far	0.01	0.03	4×10^{-4}

Accidental background rates

Prompt: $\gamma > 1\text{MeV}$ from radioactivity $\sim 40\text{Hz/AD module with shielding}$

Delayed: 1) untagged single neutron capture 2) cosmogenic beta emitters (6-10MeV, mostly $^{12}\text{B}/^{12}\text{N}$) 3) $\text{U/Th} \rightarrow \text{O, Si}$ ($\alpha, n, \gamma[6 - 10 \text{ MeV}]$)



	DYB	LA	Far
Signal rates			
1) neutrons	930/day	760/day	90/day
2) β s	18/day	12/day	1.5/day
3) $\alpha, n\gamma$	210/day	141/day	14.6/day
Coinc rate	<10/day	<10/day	<10/day
B/S	$\sim 2 \times 10^{-3}$	$\sim 2 \times 10^{-3}$	$\sim 3 \times 10^{-3}$

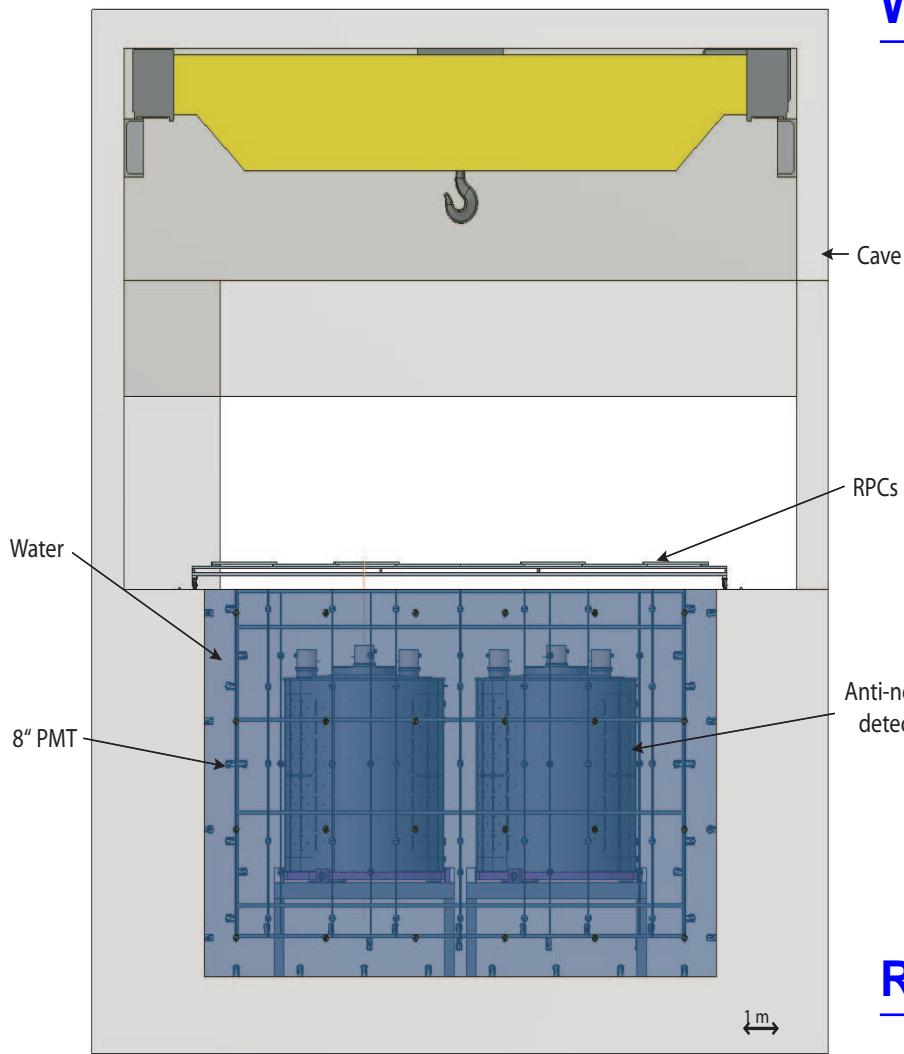
Untagged background rates are tiny and subtractable

THE DAYA BAY WATER SHIELD AND MUON VETO SYSTEM

Muon System Requirements

Item	Requirement	Justification
Thickness of water shield	$\geq 2 \text{ m}$	Attenuate fast neutrons and γ rays from rock
Total inefficiency for detecting muons	$\leq 0.5\%$	Reduce fast-neutron bkgd to a level below ${}^9\text{Li}$
Uncertainty of efficiency	$\leq 0.25\%$	Maintain fast-n uncertainty well below that of ${}^9\text{Li}$
Random veto deadtime	$\leq 15\%$	Avoid undue impact on statistical precision
Uncertainty in random veto dead-time	$\leq 0.05\%$	Keep well below other systematic uncertainties
Position resolution	0.5–1 m near AD	Study radial dependence of cosmogenic background
Timing resolution	$\pm 2 \text{ ns}$ (Cherenkov) $\pm 25 \text{ ns}$ (RPCs)	Allow spatial reconstruction of muon trajectory Limit random veto deadtime from false coincidences to $\mathcal{O}(1\%)$

The Water Shield and Muon Veto



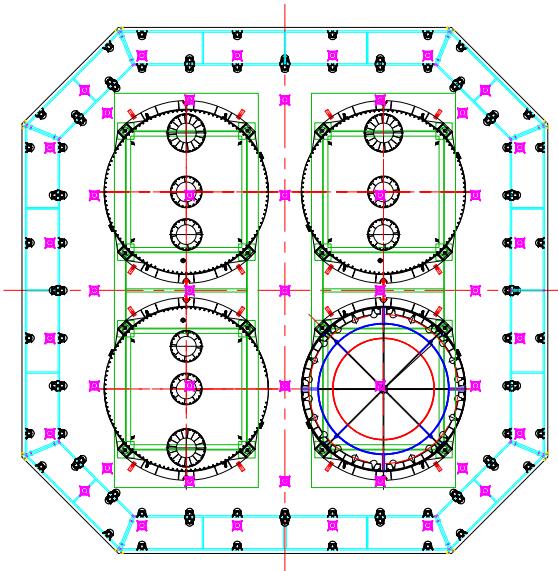
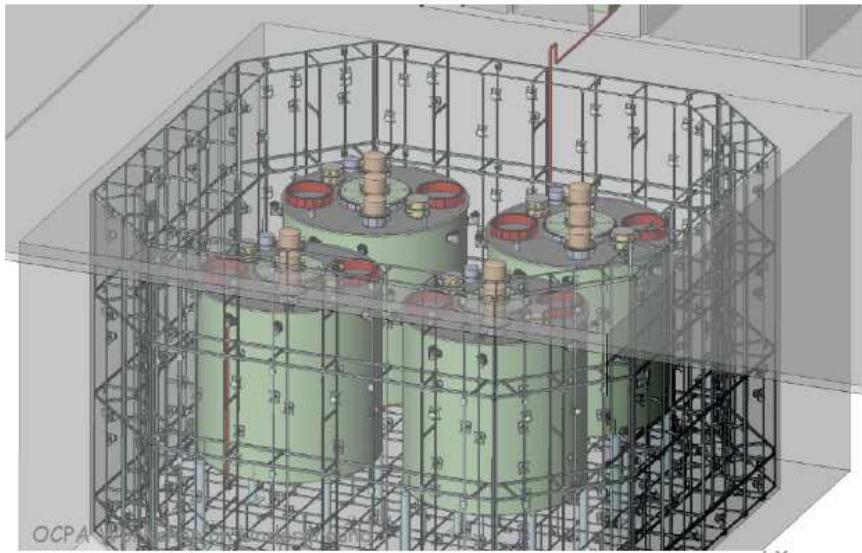
Water pool: The $\bar{\nu}_e$ detectors are immersed in a water pool with 2.5m of water on all sides.

Inner muon veto: 1m in from the sides and bottom of the pool a single layer of 8" PMTs ($1/8\text{m}^2$) acts as a water Cherenkov μ detector.

Outer muon veto: The outer 1m of the water pool is instrumented with 8" PMTs ($1/6-7\text{m}^2$). Separated by Tyvek reflectors from inner veto.

RPC system : On top of pool, multiple layers of resistive plate chambers.

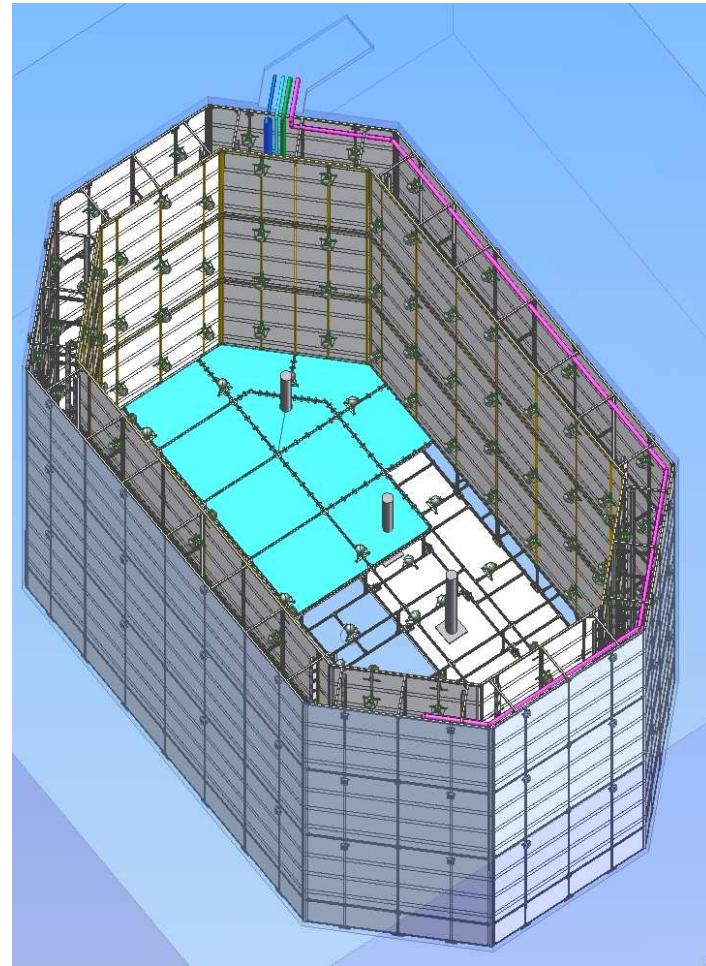
Muon Veto Details



PMT support structure - Far Hall (16x16x10m)

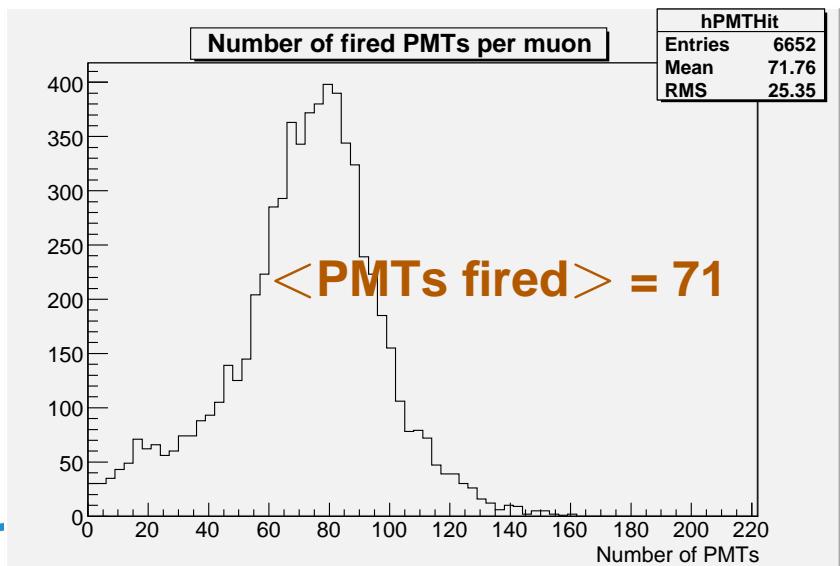
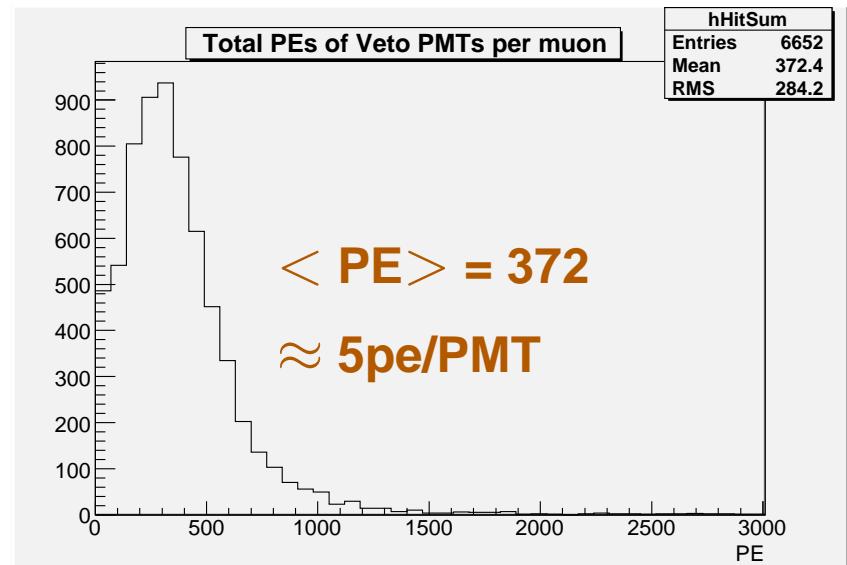
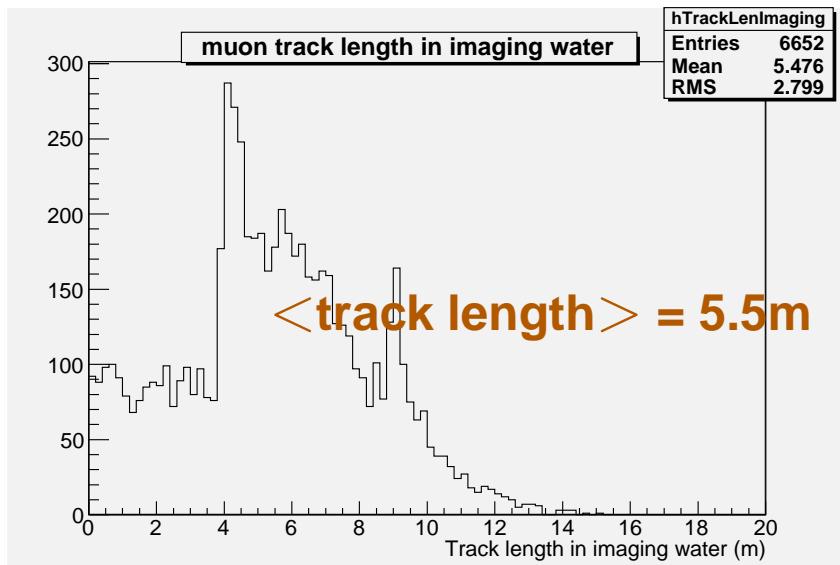
Tyvek panels line outer wall and separate inner and outer veto regions.

Near Hall layout (16x10x10m):



Inner Water Shield Simulation

Kevin Zhang, BNL



Far Site inner water shield:

Tyvek reflectivity in water = 81%

1 PMT/ 8m^2 = 0.5% coverage.

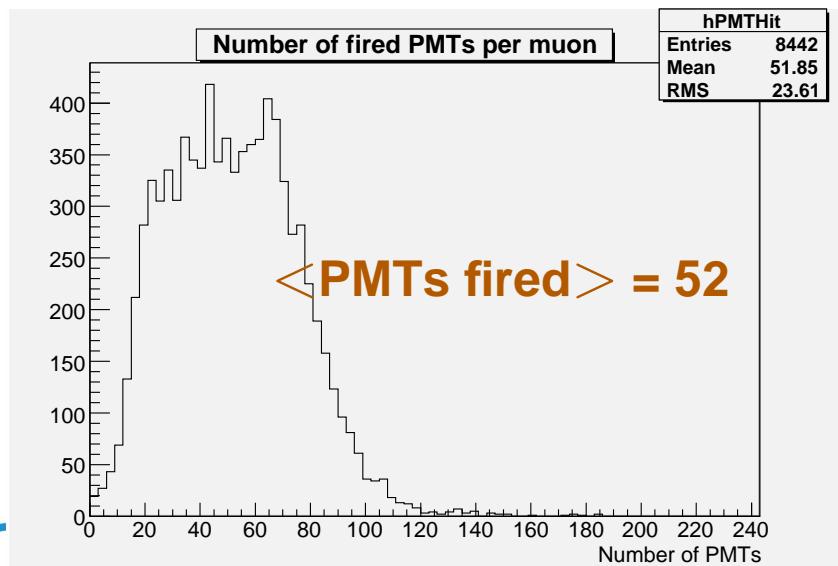
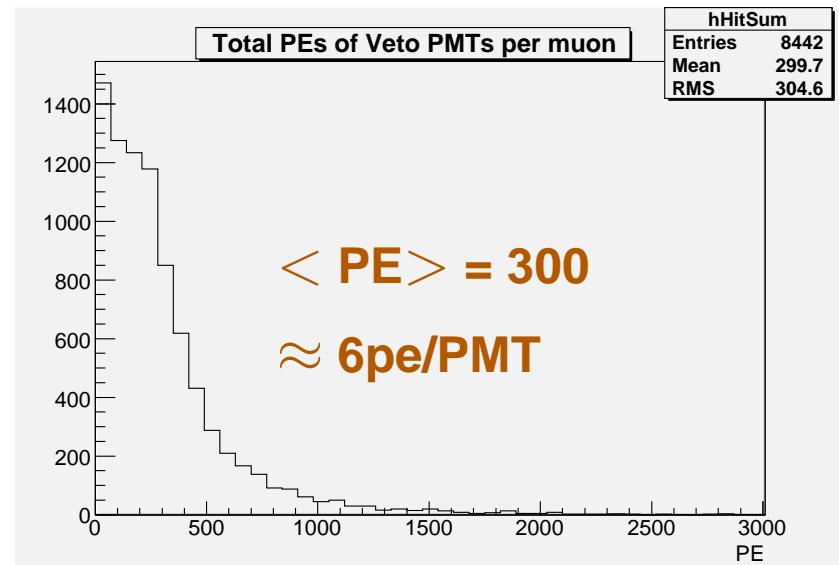
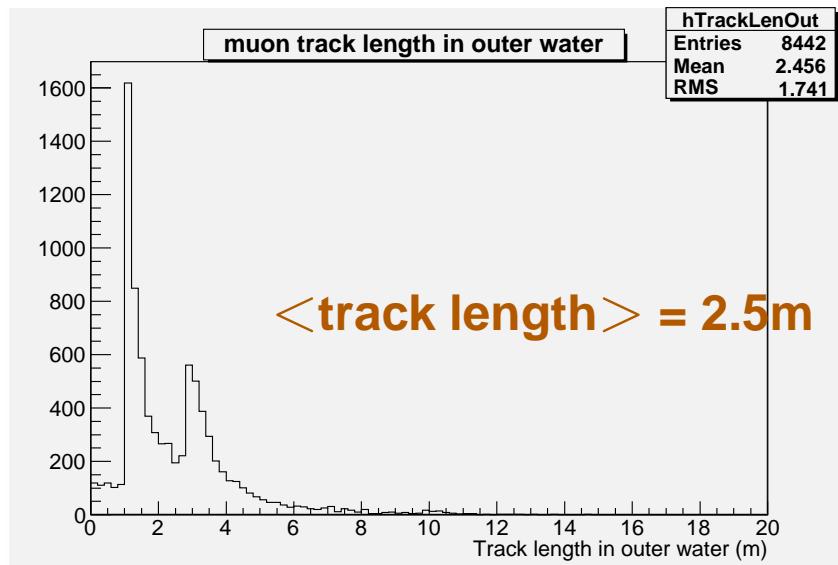
128/32 PMTs on the sides/bottom.

30m attenuation length.

PMT threshold = 0.25pe.

Outer Water Shield Simulation

Kevin Zhang, BNL



Far Site outer water shield:

Tyvek reflectivity in water = 81%

1 PMT/6-7m² \sim 0.6% coverage.

128/96 PMTs in-facing/out-facing.

30m attenuation length.

PMT threshold = 0.25pe.

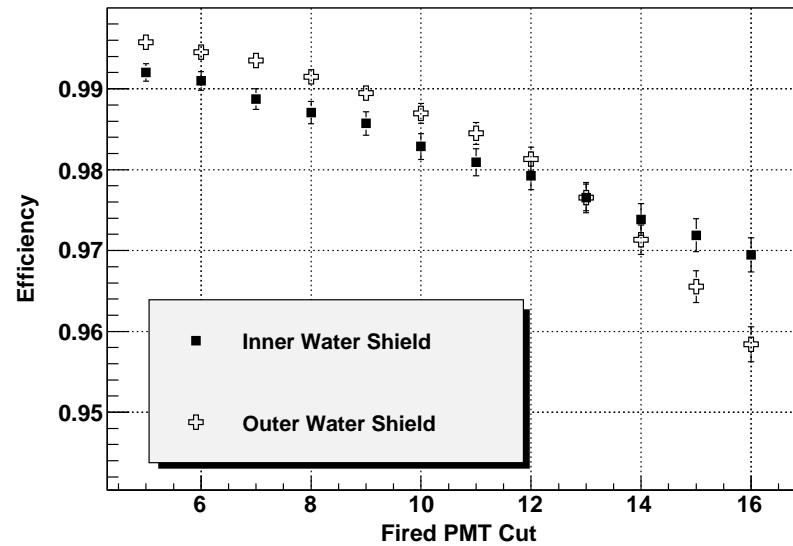
Inner Muon Veto Efficiency

Kevin Zhang, BNL

Events in AD that occur within $200 \mu\text{ s}$ of a muon trigger are vetoed to suppress cosmogenic bkgds. The baseline water shield muon trigger uses an OR of a multiplicity trigger for inner and outer shields.

Given PMT noise $\leq 50 \text{ kHz}$ and require muon veto trigger deadtime $< 1\%$.

Muon tagging efficiency as a function of number of hit PMTs:

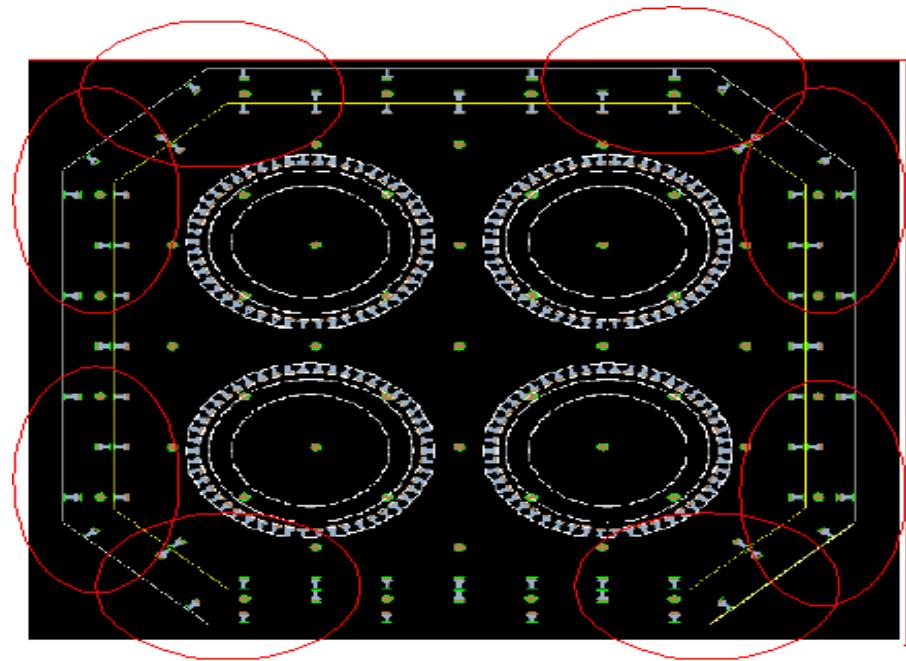
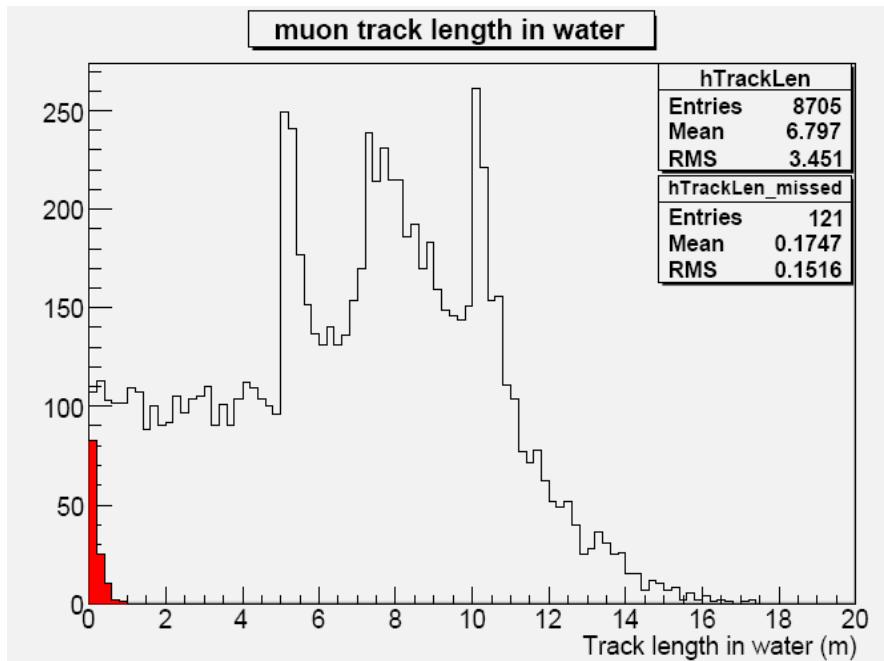


Inner veto require > 11 PMTs = 98 % tagging eff.

Total Muon Veto Efficiency

Kevin Zhang, BNL

Most inefficient muons are short tracks from outer water shield \Rightarrow use localized triggers in 8 sections of outer shield, cut on 8 PMTs fired/section:



	Pool Only	Pool+RPC
Near	$98.85 \pm 0.12\%$	$99.43 \pm 0.09\%$
Far	$98.81 \pm 0.12\%$	$99.44 \pm 0.08\%$

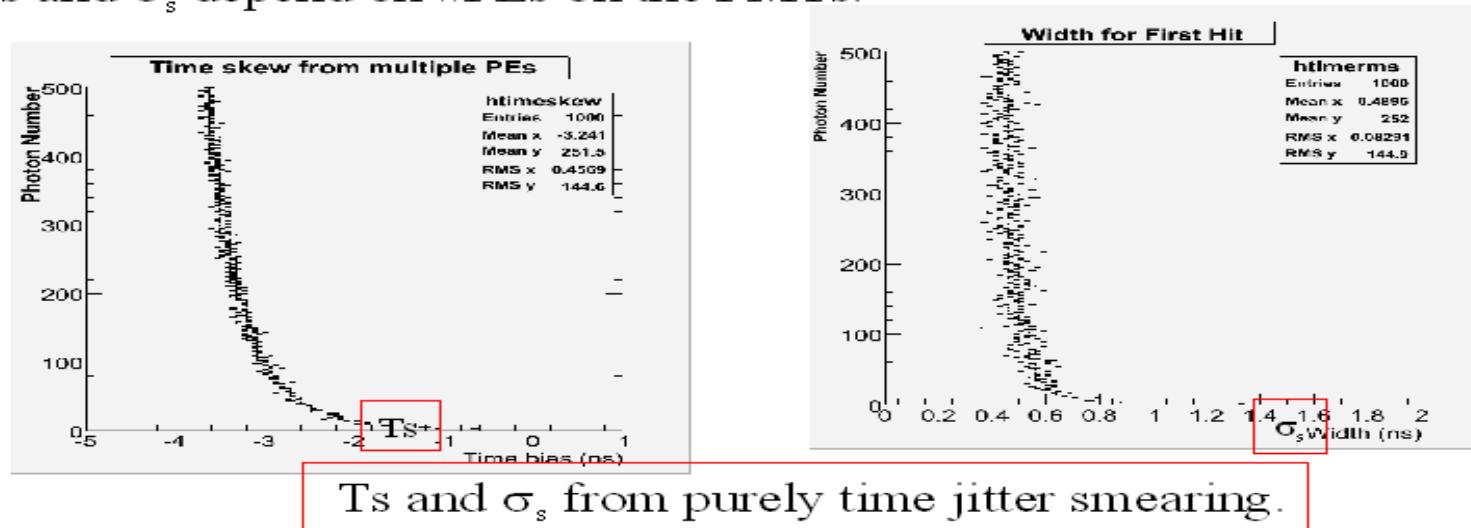
Position resolution: Fit method

Kevin Zhang, BNL

A position resolution of $\sim 0.5\text{m}$ is desirable to study radial dependence of cosmogenic backgrounds in the AD:

- Reminder: $\chi^2 = \sum_k (\Delta T / \sigma)^2$ with six free parameters used in the fitting:
 - Vertex position: (x_0, y_0, z_0) , Track angles (ϕ, θ)
 - $\Delta T = (T_f - T_i)$, T_f is the first hit time on PMT i , time jitter $\sigma = 1.2\text{ ns}$.
- Time skew factors need to be considered $\rightarrow \chi^2 = \sum_k ((\Delta T + T_s) / \sigma_s)^2$

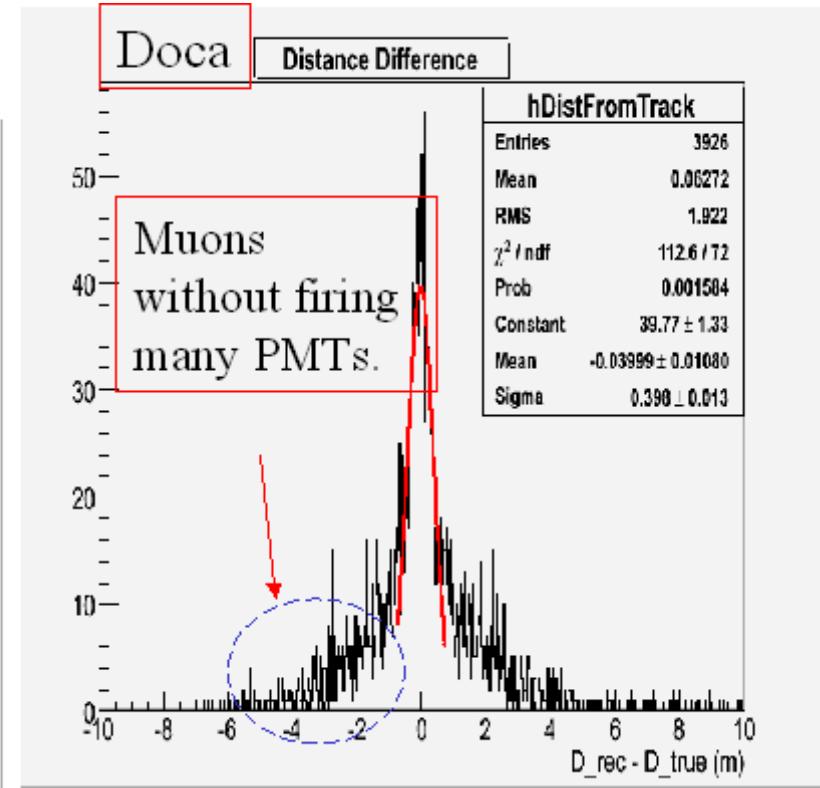
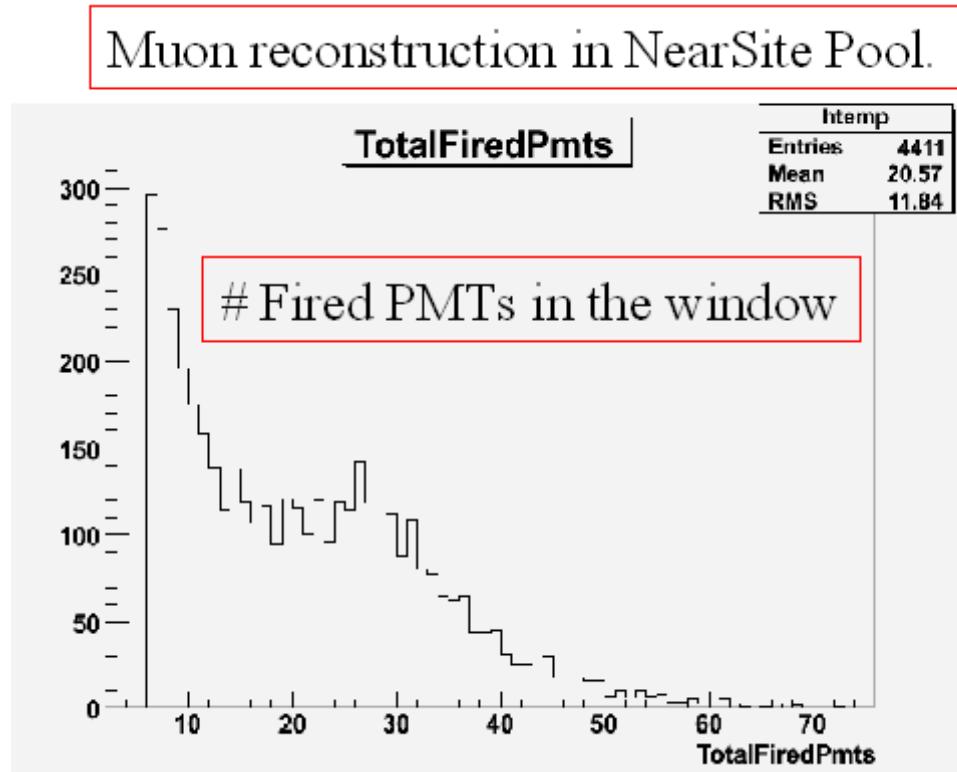
T_s and σ_s depend on #PEs on the PMTs.



Position resolution in inner shield

Kevin Zhang, BNL

PRELIMINARY fit results:



DOCA = Distance of Closest Approach to muon track.

A resolution of $\sim 40\text{cm}$ can be achieved from Inner Water shield.

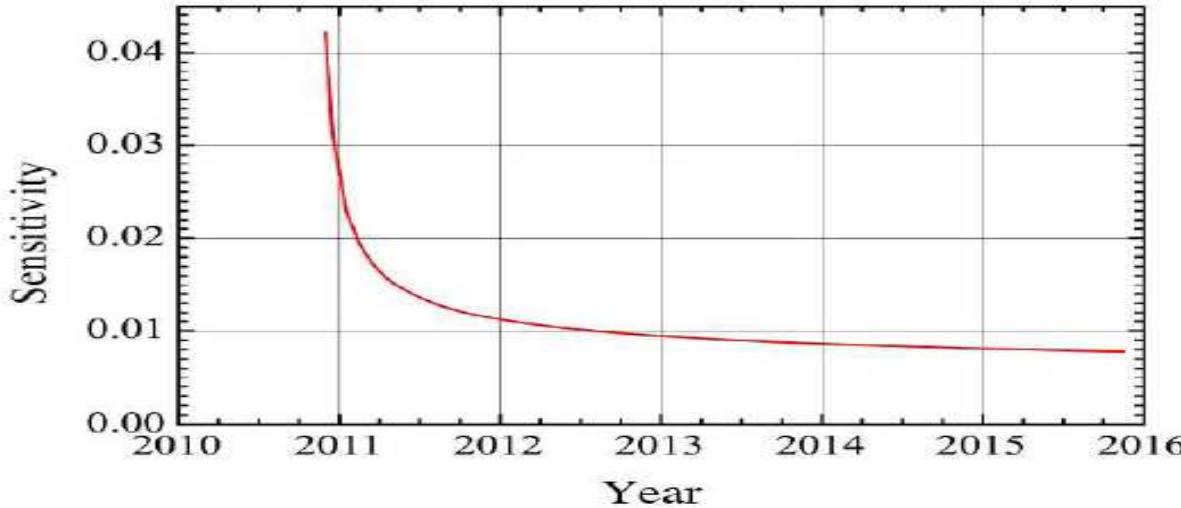
(Farsite Water pool has a similar distribution.)

TIMELINE AND SENSITIVITY

Detector systematics

Source of uncertainty		Chooz (<i>absolute</i>)	Daya Bay (<i>relative</i>)
# protons	H/C ratio	0.8	0.2
	Mass	-	0.2
Detector	Energy cuts	0.8	0.2
Efficiency	Position cuts	0.32	0.0
	Time cuts	0.4	0.1
	H/Gd ratio	1.0	0.1
	n multiplicity	0.5	0.05
	Trigger	0	0.01
	Live time	0	< 0.01
Total detector-related uncertainty		1.7%	0.38%

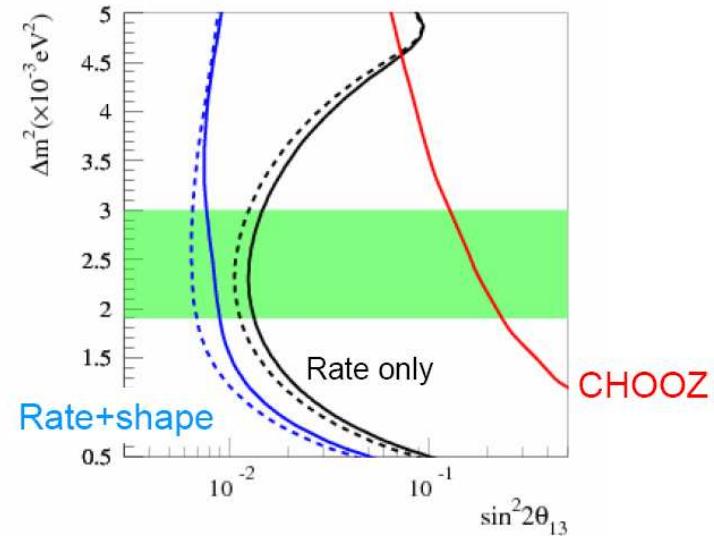
Sensitivities



← 90% C.L. limit vs time with baseline detector systematic of 0.38% 2% uncorrelated reactor power uncertainty

After 3 years running →

— baseline detector systematic 0.38%
- - - goal detector systematic 0.18%

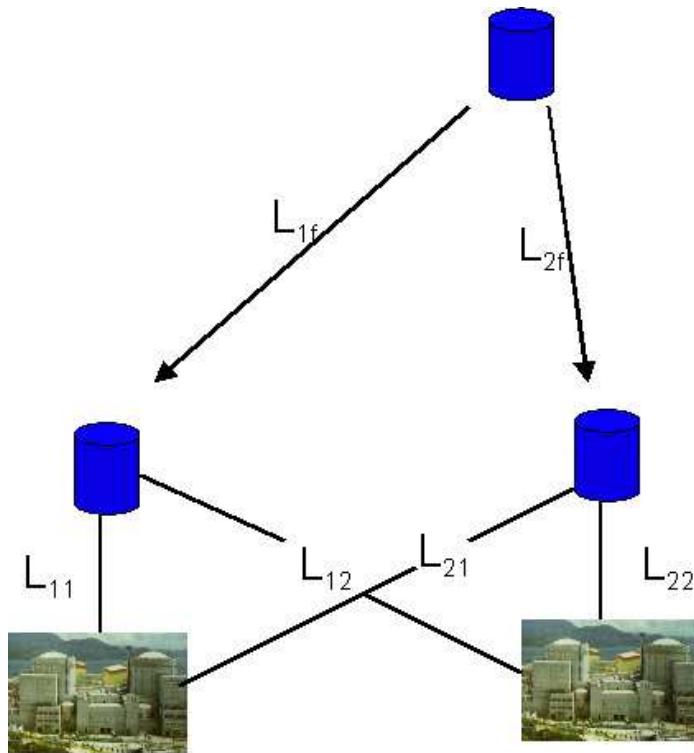


BACKUP

Near/Far cancellation

FAQ: How does the extended distribution of near cores compromise the near/far cancellation?

A: Deweigh the oversampled cores by a factor, α , Ratio = $\alpha \frac{\text{Near1}}{\text{far}} + \frac{\text{Near2}}{\text{far}}$



$$\alpha = \frac{1/(L_{22}^2 L_{1f}^2) - 1/(L_{21}^2 L_{2f}^2)}{1/(L_{11}^2 L_{2f}^2) - 1/(L_{12}^2 L_{1f}^2)}$$

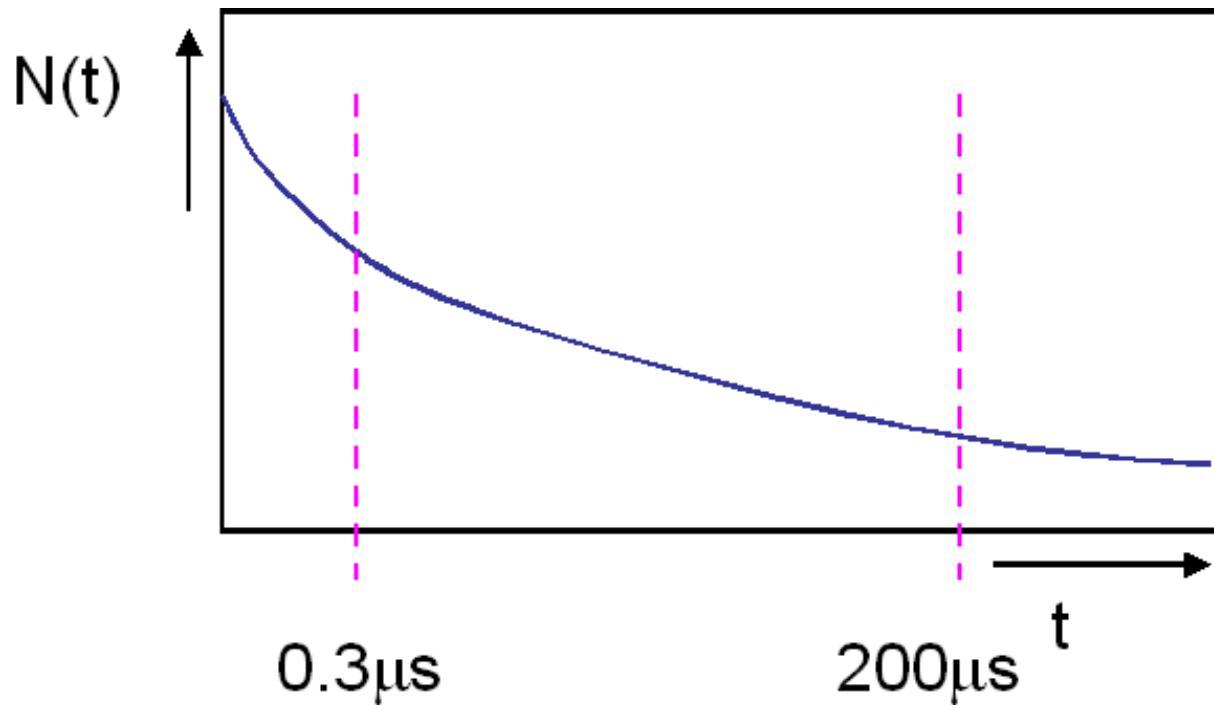
For Daya Bay 4 cores, $\alpha = 0.34 \Rightarrow$
factor 50 cancellation: 2% \rightarrow 0.035%

For Daya Bay 6 cores, $\alpha = 0.39 \Rightarrow$
factor 20 cancellation: 2% \rightarrow 0.1%

Deweighting \Rightarrow cancellation of reactor power uncertainties to better than 0.1% ..

Neutron Time Cuts

Bob McKeown



These cut times must be the same to ~ 10 ns for all modules
→ use common clock
→ 0.05% contribution to neutron efficiency

Daya Bay/Chooz comparison

Kam-Biu Luk

